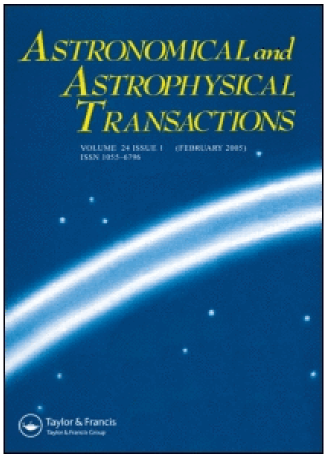

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The dedicated interferometer for rapid variability

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The dedicated interferometer for rapid variability

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A project is underway to develop a two-element interferometer for dedicated monitoring of compact radio sources. The primary goal will involve long-term, fully-sampled monitoring of a large population of extragalactic sources to study interstellar scintillation and search for extreme scattering events. The interferometer will make use of two existing 26-metre antennas with an east-west separation of about 400 metres at the Pisgah Astronomical Research Institute, in partnership with the Pisgah Astronomical Research and Science Education Centre, an interinstitutional centre of the University of North Carolina system.

Keywords: Extreme scattering events; ISM; Rapid variability

1. Introduction

A series of discoveries has revealed a rich and unexpected phenomenology in the rapid variations of compact extragalactic radio sources. Accumulating evidence points toward scattering by density fluctuations in the ionized interstellar medium (ISM) of our galaxy as the cause of the most rapid observed fluctuations, commonly manifested as intraday variablity (IDV). In addition to ubiquitous scattering, very rare extreme scattering events (ESEs) are evidently caused by discrete structures in the ISM, involving large density contrasts on very small ($\approx$ au) scales. These structures appear to be significantly overpressured with respect to the ambient ISM, and may be transient phenomena. The nature and origin of the structures responsible for ESEs is unknown.

Fully probing IDV over many lines of sight and unraveling the mystery of ESEs requires dedicated monitoring of a large sample of compact extragalactic sources. By their very nature,

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national observatories are not well suited for such programs. We are therefore developing the Dedicated Interferometer for Rapid Variability (DIRV) at the Pisgah Astronomical Research Institute (PARI) near Rosman, North Carolina, USA.

2. The need for dedicated monitoring

Compact extragalactic radio sources typically exhibit variations both intrinsic to the source and extrinsic, the latter almost certainly caused by scintillation in the ionized ISM. The intrinsic variations were first recognised as such [1, 2], but other variability phenomena variously labeled low-frequency variability [3–6] (LFV), flicker [7], and IDV [8] generally presented a serious challenge to the intrinsic explanations. In the context of intrinsic models, LFV, flicker, and IDV implied brightness temperatures in emission components significantly in excess of the 10^{12} K Compton limit for incoherent synchrotron emission [9].

The realisation that compact extragalactic sources should exhibit refractive interstellar scintillation offered an important clue for much, if not all, of the ‘anomalous’ variability [10, 11]. The origin of IDV continued to be debated, particularly in reference to sources showing rapid polarization changes [12] and correlated radio-optical variability in B0716 + 715 [13, 14].

Recent discoveries, however, that several sources show annual cycles in their IDV timescales and amplitudes [15–18] conclusively demonstrate that interstellar scintillation (ISS) is responsible for the observed IDV in these objects. In these cases, the sky projections of the scintillating screen velocity and the Earth’s orbital velocity come close to canceling once per year resulting in an increased scintillation timescale, compared with shorter timescales six months later. Also, the detection of small delays in the fluctuations of several sources over intercontinental distances adds further support to the ISS hypothesis [19–21].

The near ubiquity of ISS then leads to the expectation that most compact sources will exhibit this phenomenon, most often as IDV. Thus, these sources can be used to probe density fluctuations in the ionized ISM over numerous lines-of-sight sampling regions of the galaxy generally inaccessible with pulsar observations. In addition to constructing a global picture of the distribution of turbulence in the galaxy [22], such observations would address a number of specific issues, including (i) nearby screens, which produce the fastest variations [18, 23]; (ii) Earth orbit synthesis, in which annual variations in the scintillation pattern provide a probe of intrinsic source structure on $\approx$10 μas scales [24]; and (iii) scattering limits to VLBI resolution, which affect the smallest components, *i.e.* those responsible for the majority of the scintillating flux in a source.

A most remarkable, and unexpected, manifestation of interstellar scattering consists of ESEs – brief periods of strong fluctuations distinct from a source’s typical variations. ESEs are evidently caused by enhanced scattering in localised compact structures in the ISM [25, 26]. Figure 1 shows the remarkable discovery event in 0954 + 658 that Lazio has aptly termed ‘the prototypical and exemplary’ ESE. (See http://ese.nrl.navy.mil.) The highly dispersive nature of this event and others clearly demonstrate that plasma refraction is responsible. The light curve at 2.7 GHz is characteristic of most ESEs, showing a broad minimum preceeded and followed by enhanced flux, evidently scattered from mid-event. The sharp cutoffs evident in 0954 + 658 at 2.7 GHz bracketing the broad minimum are most readily interpreted as the passage of a caustic. The fall/rise time associated with caustic passage, combined with the known VLBI structure [27], allows the proper motion of the focusing cloud to be determined. For distances of $\approx$500 pc, this yields transverse velocities characteristic of interstellar motions ($\approx$50 km/s). Extragalactic distances are all but ruled out by the large transverse velocities required [25].

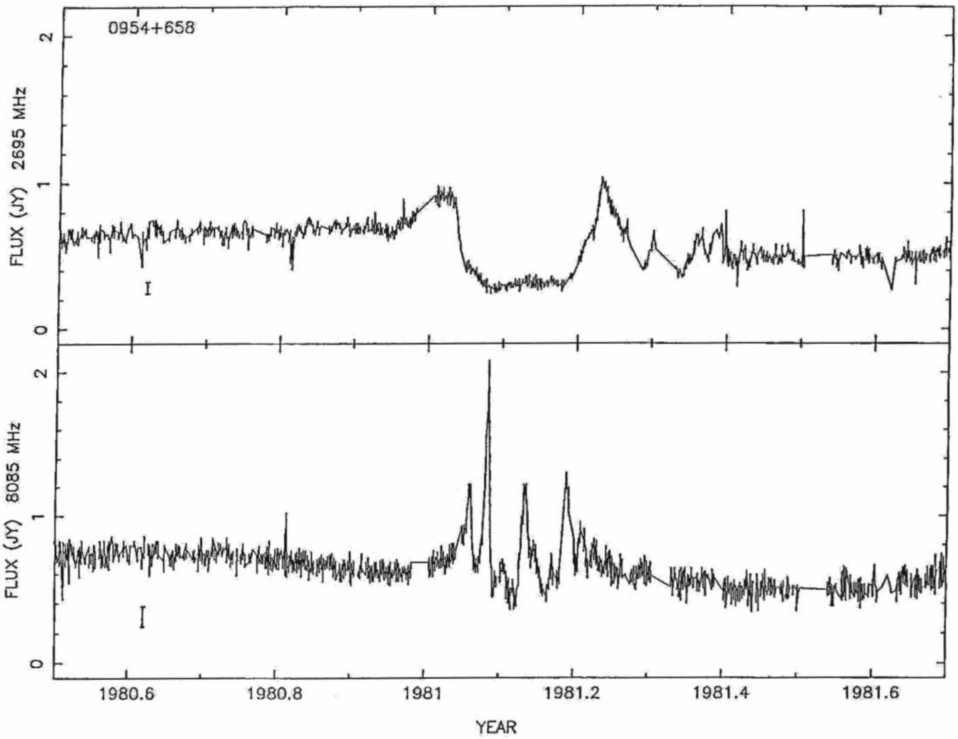

Figure 1. Extreme Scattering Event in 0954 + 658. The minimum at 2.7 GHz is thought to be due to flux scattered away from the causative cloud. Some of this scattered flux shows up as increased flux before and after minimum. The sharp drop and rise preceding and following the minimum at 2.7 GHz may be caused by a caustic. At 8.1 GHz the scattering angles are almost an order of magnitude smaller and thus radiation probes the central parts of the cloud where it apparently encounters smaller scale focusing structures resulting in sharp spikes. From Fielder *et al.* [25].

The focusing mechanism and assumed distance lead to an estimate of the transverse gradient of the column density in the cloud. Estimating the density enhancement is uncertain, however, since the cloud geometry is unknown. Assumed isotropic structure leads to quite remarkable density enhancements of $\approx 10^3\,\mathrm{cm}^{-3}$ on scales of 10^{13} cm. These estimates can be reduced by assuming that the cloud is extended along the line of sight, for example in a filamentary or sheetlike geometry, but in any case, the clouds are far from pressure equilibrium with the ambient ISM and could be expected to expand rapidly and dissipate. This naturally suggests that the 'clouds' are transient phenomena; cooling substructure associated with shocks crossing the line of sight has been suggested as an explanation [28]. An alternative hypothesis posits that the clouds are in internal gravitational virial equilibrium, with the implication that the galactic population of ESE-producing clouds harbors a significant portion of the galaxy's dark matter [29].

Only a few dozen ESEs have been detected, [26, 30–32] in addition to several discovered as fluctuations in pulsar intensity and group delays [33, 34]. Clouds more distant than their characteristic focal lengths apparently form observable caustics, while those closer typically show rounded minima in their light curves. The distribution of events on the sky suggests that ESEs may occur preferentially toward loops in the foreground galactic nonthermal radio emission, as might be expected if the structures responsible are associated with the peripheries of supershells swept out by supernovae and stellar outflows [26]. In only one case (toward 1741-038) has it been possible to trigger and carry out related observations during the event. VLBI observations revealed an increase in apparent source size consistent with stochastic scattering within the ESE-producing cloud [30]. Unfortunately, these observations were of limited dynamic range.

Overall, ESEs occur at the rate of approximately one event per 50 source years; thus dedicated monitoring of many compact sources is required to discover new events. As discussed above, we may expect a somewhat higher event rate near loops in the galactic nonthermal radio foreground. ESEs were originally discovered as a byproduct of the US Naval Observatory Earth rotation program using the NRAO Green Bank 3-element interferometer [25]. Subsequently, six months of 300-foot time were dedicated to discovering additional ESEs in a sample of about 150 compact sources [26]. The Green Bank Interferometer continued monitoring until 1996 with funding external to the NRAO [31]. This led, for example, to the discovery of the ESE in 1741-038, the only case for which concurrent observations could be carried out.

ESEs remain a significant mystery. The nature of the causative structures in the ISM is unknown. Are ESEs a manifestation cooling substructure in shocks [28], or do they indicate the presence of a new population of galactic structures [29]? Addressing these questions will require the discovery of additional events with triggered concurrent observations such as optical photometry [35], HI absorption [31], Faraday rotation, etc. Perhaps most important will be VLBI imaging since the refractive scattering mechanism necessarily implies image distortion, and in those cases involving caustics, multiple imaging. In the only VLBI study of a source undergoing an ESE, Lazio *et al.* [30] pointedly conclude, 'The major impediment to a set of such observations is the lack of an existing monitoring program that could find additional ESEs.'

Should we find that ESEs are caused by interstellar shocks, then we shall have a unique probe of shock substructure on approximately au scales and smaller. No other foreseeable observation would be able to resolve details about the ionized density profile through an interstellar shock. We also need to understand how this phenomenon fits into the larger astrophysical context of the ISM: What are the interstellar environments most conducive to ESEs [36]? Are the statistics of ESEs consistent with the expected abundance of interstellar shocks [28]? Do ESEs, in fact, occur preferentially near the edges of superbubbles [26]?

Determining the nature of ESE-producing structures and using ISS as a probe of the galaxy now requires dedicated monitoring of a large sample of compact extragalactic sources. Such observations are well outside the scope of feasibility within the national observatory system, in which highly versatile instruments are used for a wide range of projects. In this context, we undertook to develop a dedicated instrument. A single observation program can simultaneously monitor ISS variations as well as serve as a trigger for comprehensive ESE observations.

3. Development of the interferometer

The ideal instrument for monitoring sources at GHz frequencies is an interferometer. The challenge of using these measurements stems from the fact that the signal from a 1 Jy source is characteristically only a few tenths of a percent of the total system power. An interferometer exploits the voltage correlation inherent in the source signals from the individual antennas. This is superior to single dish measurements in which even small gain fluctuations on the timescale of a scan and confusing sources can frustrate radiometric measurements. It is worth emphasising that the sources we propose to monitor will be unresolved and exhibit known fringe frequency and phase. The confusion signal comes from typically more than one source in the primary beam [37] and is thus partially cancelled in a simple interferometer. Because aperture synthesis is not the goal of these measurements, a two-element interferometer will suffice.

DIRV will use two 26-metre antennas at PARI, separated by approximately 400 metres on a nearly east–west baseline. They were originally constructed by NASA for space communications and tracking. Both telescopes have been retrofitted by DFM Engineering for sidereal pointing and tracking. The development of DIRV is a project of the Pisgah Astronomical Research and Science Education Centre (PARSEC), an interinstitutional centre of the University of North Carolina system, working in partnership with PARI. Monitoring of compact extragalactic radio sources will be interleaved with regular pulsar timing observations at 327 MHz conducted with one 26-metre antenna through a Furman University/PARI collaboration.

The interferometer will use two dual-frequency, dual-circular-polarization feeds recently loaned to PARI on a long-term basis by the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia, USA. These feeds will permit simultaneous full Stokes measurements at approximately 2.2 GHz (S-band) and 8.3 GHz (X-band). These are second generation feeds from the Green Bank Interferometer [38] and match the f/0.42 prime focus optics of the PARI telescopes.

The frequencies of 2.2 and 8.3 GHz will allow us to sample IDV in most moderate to high latitude sources in two distinct regimes: strong scattering with refractive scintillations at S-band and weak scattering with diffractive scintillations at X-band. ESEs tend to be quite strong around 2 GHz. (At lower frequencies larger intrinsic component sizes may quench these events; at higher frequencies the scattering is appreciably weaker.) The X-band provides a means of confirming the characteristic dispersive signature of these events. In addition, observations at these frequencies will facilitate comparison with the existing long-term database of Green Bank Interferometer flux measurements [39]. In addition to obtaining polarization information, the full Stokes capability will avoid the systematic errors inherent in single polarization measurements of polarized sources and improve the signal-to-noise ratio in the measured total flux. Observing efficiency is enhanced by observing both polarizations and two widely separated frequencies simultaneously.

For simplicity of design and operation, we have eschewed using cryogenically cooled receivers; rather, we emphasize overall gain stability. This design philosophy is guided by the primary mission of DIRV to monitor small changes in the radio fluxes of extragalactic sources. The performance of the RF amplifiers is particularly critical. We have extensively tested both S-band and X-band low-noise amplifiers (LNAs) purchased from Kuhne Electronics (Germany). The amplifiers were placed in a temperature-regulated chamber and their gain and noise temperature were monitored as a function of temperature. The measured gain-temperature coefficients were about $\approx 0.5\%\,\mathrm{K}^{-1}$ (S-band) and $\approx 0.2\%\,\mathrm{K}^{-1}$ (X-band). At constant temperature, both amplifiers exhibited rms-intrinsic gain fluctuations of less than 1% over a four hour period. Our measurements indicate decreased gain fluctuations after a warmup period of several hours.

Temperature regulation will be achieved by enclosing each receiver and feed stem in a cartridge that mounts in the front end box of a 26-metre antenna. The cartridges have been designed and the first constructed with the feed attached. Our goal is to achieve ≈ 1 K temperature control in the feed box and ≈ 0.1 K control inside the cartridge. Using Peltier heat pumps and available control circuitry in conjunction with a mock-up front end box and an inner simulated cartridge we have achieved this level of temperature control in the lab.

We have begun a deep survey of radio frequency interference (RFI) at the PARI site. Results thus far indicate that the bands 2.0–2.3 GHz and 8.0–8.4 GHz are relatively free of interference originating off-site. An on-site source of computer clock emissions at ≈ 2.1 GHz can be directly addressed. The greatest concerns are at S-band and involve XM and Sirius satellite radio transmissions at 2.32 GHz and above and PCS cell phone transmissions below 1.99 GHz.

The RF signals will be amplified at the feed and transmitted to the correlator room over single mode optical fibre. This will allow us to situate the local oscillators, mixers, IF amplifiers and filters in a compact, shielded, and readily accessible location. The fibre will introduce a temperature-dependent phase delay [38], which will be corrected in the post-correlation coherent-averaging process. In addition, polarization effects can introduce small $\approx 1\%$ rms fluctuations in the received optical signal. This occurs through the interaction of linearly polarized light launched into the fibre with angled and curved interfaces at the photodetector used to reduce reflected signals [40]. As the fibre is twisted due to telescope motions the polarization orientation varies, resulting in small variations in the power passed to the photodetector. Fortunately, the ratio of modulated voltage to total optical power is not affected, and thus we plan to record the photodetector current, which is proportional to the received optical power. This information can then be used to correct the measured fringe visibilities.

At S-band, the demodulated analog S-band signals will be mixed to a frequency close to baseband for digitization and correlation. The total bandwidth sampled at S-band will be 200 MHz. Both circular polarizations from each telescope are included and correlations will be produced in all four combinations: LCP-LCP, RCP-RCP, LCP-RCP, and RCP-LCP.

At X-band, the signals will be downconverted in two stages in the correlator room (figure 2). By this procedure, we will extract two adjacent 200-MHz-wide bands, corresponding approximately to 8.0–8.2 GHz and 8.2–8.4 GHz. In the first stage of downconversion we will use the cutoff of the circular X-band waveguide in the feed (at ≈ 7.5 GHz) for image rejection. Both bands extracted will be independently correlated, each producing all four polarization combinations.

The correlation will make use of digital signal processing hardware developed by the Berkeley group [41], in particular the Berkeley Emulation Engine-2 (BEE-2). The system will be configured to provide three independent correlation streams for the three frequency bands (one at S-band and two at X-band, figure 2). Each correlation stream will receive signals from the two telescopes in both LCP and RCP via an InfiniBand BreakOut Board (IBOB) with two dual-channel ADC units sampling at 1 Gs/s. Thus, each dual channel ADC will digitize both LCP and RCP from a telescope, to be passed to the correlator via the IBOB. Each of the four correlation streams will produce four independent sets of fringes corresponding to all polarization combinations. The correlation will be functionally equivalent to an FX correlation, resulting in fringes over 1024 frequency channels for each of the four polarization combinations. The integration time will be 0.1 s. At the end of each integration, 4096 complex fringe visibilities per correlation stream will be written to disk for post-processing. These 4096 fringe visibilities consist of the 1024 frequency channels across the band times the four polarization combinations. This process will occur for each of the three frequency bands.

This approach has several distinct advantages. The bandwidth of each channel is only 200 kHz and thus the coherence length, ≈ 1.5 km, is considerably longer than the baseline, eliminating the need for delay tracking in the RF/IF or correlation. Also, RFI can be identified in the spectrum and excised prior to averaging. The integration time (0.1 s) is the maximum allowable without significant loss of fringe amplitude.

Post-correlation processing will be far less demanding in terms of computational speed and will be initially tested on a cluster of eight dual-core, 64-bit AMD processors at UNCA. The data from one scan (≈ 5 min duration) will consist of 12 arrays of complex visibilities. Each array has dimensions 1024×3000, corresponding to the number of frequency channels and integration intervals in a five-minute scan. Four polarization combinations for each of three frequency bands yields 12 arrays. The initial step will involve statistical identification of visibilities with excessive modulus, presumed to be caused by RFI. After excision of visibilities affected by RFI, each array will be coherently averaged, incorporating phase corrections for geometric and electrical delays. The resulting visibilities will then be corrected for digitization,

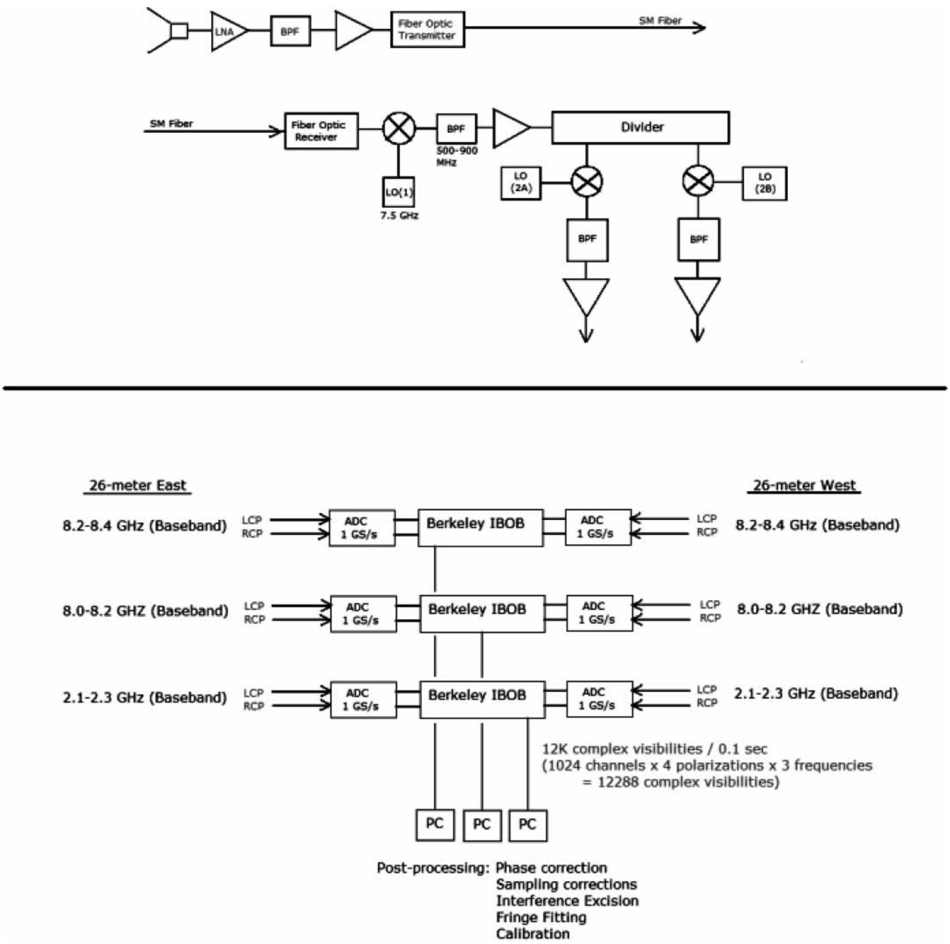

Figure 2. X-band receiver system (upper panel) and correlator system (lower panel). The X-band RF/IF analog signal path is shown for a single polarization from one antenna. The RF signal is amplified and transmitted to the correlator room via optical fibre then downconverted and split into two near-baseband signals corresponding to adjacent RF bands for digitization. The correlator system is based on the Berkeley Emulation Engine-2 (BEE-2). Each frequency band is handled through an InfiniBand BreakOut Board (IBOB) connected to the BEE2.

sampling interval size (in both frequency and time), and time-variable losses in optical transmission of the RF signals. These magnitude corrections are all small. Existing connections will permit transfer of correlated data.

After RFI excision and coherent averaging, each scan will yield 12 fringe visibilities for the four polarizations and three frequency bands. The subsequent stage of analysis will then apply flux and polarization calibration to these visibilities resulting in the full set of measured Stokes parameters. This stage will encompass data from a full calibration cycle, typically over a sidereal day.

4. Conclusions

DIRV will enable dedicated monitoring of IDV and searching for ESEs in compact extragalactic radio sources. Such a facility is not feasible within the national observatory infrastructure given the national observatories' necessary and commendable comittment to serving a broadly based scientific community with diverse science needs. Thus, DIRV will complement the function of the national observatories.

Monitoring IDV along many lines of sight to extragalactic sources will enable studies of the distribution of turbulence in the galaxy and provide the data required to address a variety specific issues, including the nature and distribution of nearby screens, and using Earth-orbit synthesis to probe the most compact structures in the cores of radio-emitting active galactic nuclei.

ESEs remain an unsolved problem. The key to understanding ESEs lies in discovering more events and probing the line of sight during and after an event. Thus, the detection of an ESE with DIRV would trigger VLBI imaging and other observations designed to detect intervening matter through neutral hydrogen absorption, optical extinction, Faraday rotation, etc. Because so little is known about the causative structures, the results of such observations will be highly informative.

The PARSEC–PARI partnership brings together university faculty and students and PARI staff in a collaborative environment which is necessarily instrumentation-oriented. This is an excellent opportunity for students to gain valuable hands-on experience in the development and use of a research instrument.

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